Life Estimation of High Level Waste Tank Steel for F-Tank Farm Closure Performance Assessment

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Outline

- Performance assessment for tank closure
- Tank life estimation technical approach
  - Deterministic
  - Stochastic
  - Corrosion Mechanisms
- Results
- Recommendations

Tank Closure Performance Assessment

- Performance assessment supporting closure of F-Tank Farm

- Carbon steel of high level waste tank initially provide a barrier contaminant escape
- Corrosion mechanisms will degrade liner over time
- Liner will no longer provide a barrier

- Estimate the time to failure of the tank liner due to corrosion processes

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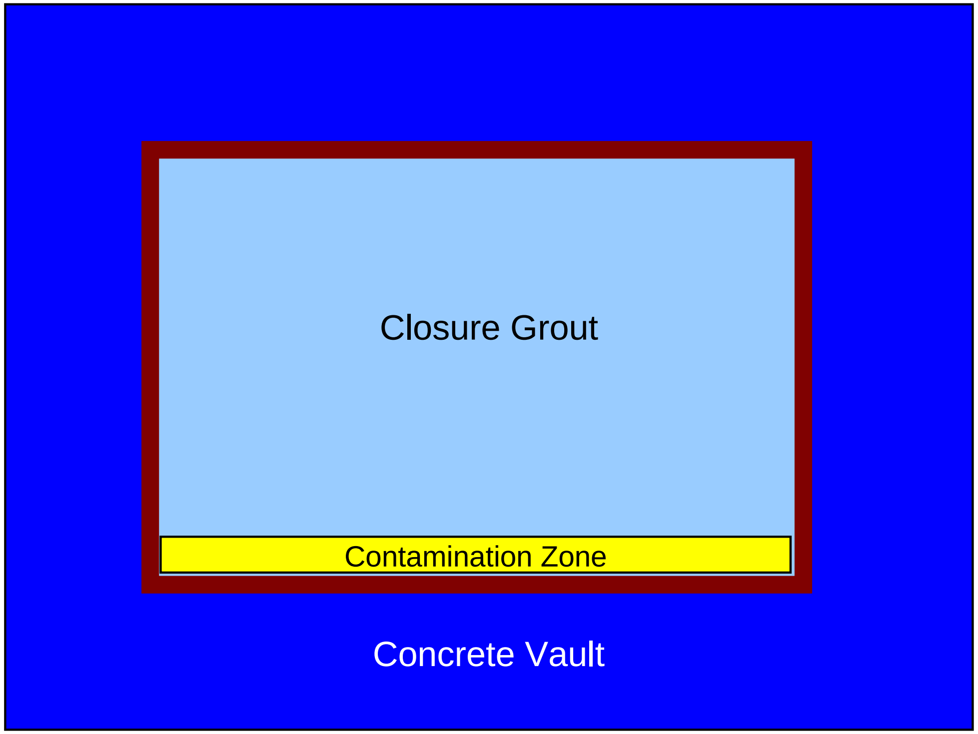
Life Estimate: Deterministic Approach

- Active corrosion mechanisms on the steel under closure conditions
- Assumption of only one liner

- Exposures
  - Contamination Zone
  - Grout/Concrete Vault



Contamination Zone

- Function of the undissolved solids in the residual on tank bottom
- R-value: Ratio of inhibitor species (nitrite and hydroxide) to aggressive species (nitrate + chloride)
  - High R-values: Minimal Corrosion
  - Low R-values High corrosion due to insufficient inhibitors
- Results indicate no accelerated corrosion from contamination zone
- Corrosion rate of 0.04 mils/year (1μm/year) assumed

Tank	R-Value
1	5.47
2	4.36
3	3.94
4	9.67
5	5.31
6	12.39
7	3.44
8	3.87
17	3.18
18	4.51
19	0.24
20	3.18
25	3.19
26	3.19
27	3.19
28	3.19
33	4.53
34	12.40
44	4.45
45	3.19
46	3.19
47	3.19

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Corrosion in Concrete/Grout

- Corrosion of steel exposed to concrete/grout occurs by a complex mechanism that occurs through metal dissolution at the concrete/metal interface.
- Concrete generally prevents corrosion of the steel
  – Forms passive oxide on the steel surface
  – Maintains a high pH environment
  – Provides a matrix resistant to diffusion of aggressive species
- Passivity can be lost through carbonation or through <u>chloride induced film</u> breakdown
  – Pore water characteristics change with the introduction of chlorides or carbon dioxide, the passive film on the steel may break down

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Carbonation

- Pore water pH reduces dramatically due to the conversion of the calcium hydroxide to calcium carbonate through reaction with carbon dioxide

$$Ca(OH)_2 + CO_3^{2-} \Rightarrow CaCO_3 + 2OH^-$$

- Complex function of the permeability of the concrete, relative humidity, and the carbon dioxide availability

- Simple Model

$$X = \left(D_i \frac{C_{gw}}{C_g} t \right)^{\frac{1}{2}}$$

- Assumption: subsurface concrete vaults water saturated
- CO_2 transport is in the aqeuous phase.

X	=	carbonation depth (cm)
D_i	=	intrinsic diffusion coefficient of Ca^{++} in concrete (cm^2/s)
C_{gw}	=	total inorganic carbon in ground water ($mole/cm^3$)
C_g	=	$Ca(OH)_2$ bulk concentration in concrete solid ($mole/cm^3$)
t	=	time (s)

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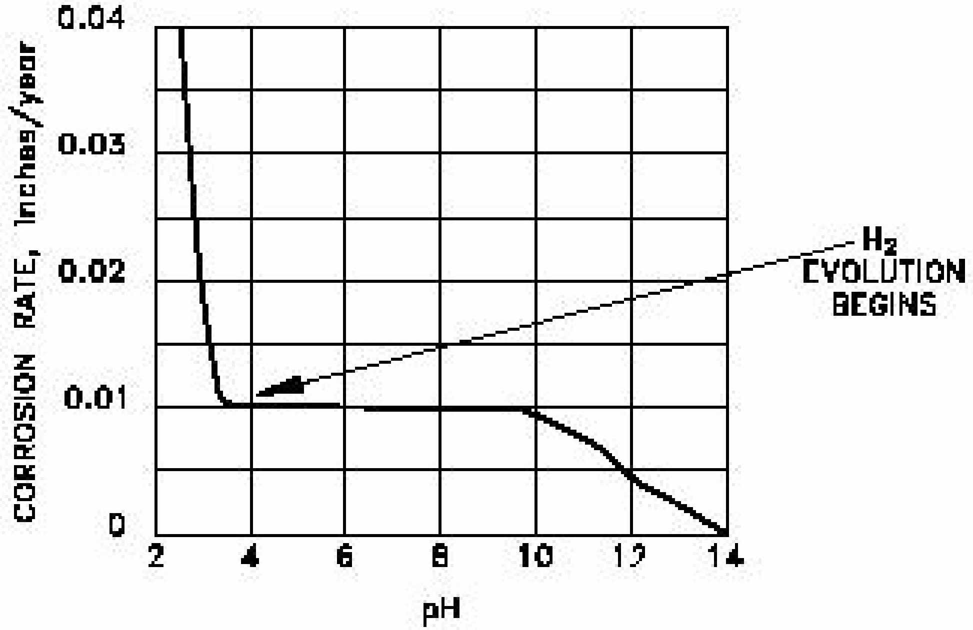
Effect of Carbonation

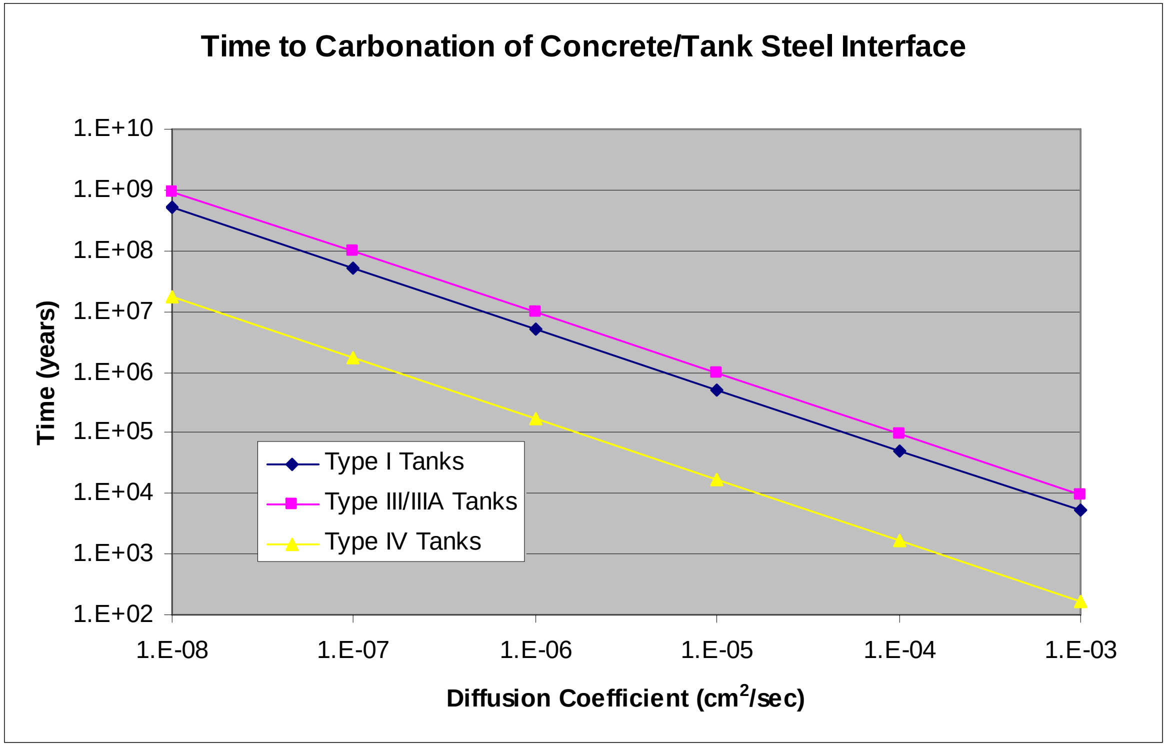
- Reduction of the pH into a regime where the steel is susceptible to corrosion



EFFECT OF pH ON THE CORROSION OF IRON
EXPOSED TO AERATED WATER AT ROOM TEMPERATURE

Carbonation Times

Parameter	Value
Type I Tank Minimum Concrete Vault Dimension	22-in.
Type III Tank Minimum Concrete Vault Dimension	30-in.
Type IV Tank Minimum Concrete Vault Dimension	4-in.
D_i (Ca^{++})	1E-8 cm^2/sec $\leq D_i \leq$ 1E-3 cm^2/sec
C_{gw} (as soil moisture content)	1.93E-7 mol/cm^3
C_g	0.02 mol/cm^3



Chloride Induced Corrosion: Initiation

- Due to the breakdown of the passive film, thereby indicating that chloride diffusion is the rate controlling step for corrosion initiation

- Followed by oxygen diffusion for corrosion reactions to occur

- Simple Empirical Model:

$$t_{initiation} = \frac{129 \cdot t_c^{\,1.22}}{WCR \cdot \left[Cl^-\right]^{0.42}}$$

$t_{initiation}$ = time required for initiation (years)
t_c = thickness of the concrete cover (in.)
WCR = water-to-cement ratio
[Cl-] = chloride concentration in the groundwater (ppm)

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Chloride Induced Corrosion: Reaction

- Oxygen diffusion to breakdown of passivity

$$Fe + \frac{3}{2} H_2O + \frac{3}{4} O_2 = Fe\left(OH\right)_2$$

- Corrosion rate

$$R_{corrosion} = \frac{4}{3} N_{O_2} \frac{M_{Fe}}{\rho_{Fe}}$$

M_{Fe} = molecular weight of iron (56 g/mol)
ρ_{Fe} = density of iron (7.86 g/cm3)

$$N_{O_2} = D_i \frac{C_{gw}}{\Delta X}$$

N_{O2} = Flux of oxygen through concrete (mol/s/cm^2)
D_i = Oxygen diffusion coefficient in concrete (cm^2/sec)
C_{gw} = Concentration of oxygen in groundwater (mol/cm^3)
ΔX = Depth of concrete (cm)

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Chloride Induced Corrosion: Input Parameters

Parameter	**Value**
Type I Tank Minimum Concrete Vault Dimension	22-in.
Type III Tank Minimum Concrete Vault Dimension	30-in.
Type IV Tank Minimum Concrete Vault Dimension	4-in.
WCR	0.6
$[Cl^-]$	2-100 ppm
D_i (Oxygen)	1E-8 $cm^2/sec \leq D_i \leq$ 1E-3 cm^2/sec
C_{gw} (Oxygen)	7.25 mg/L

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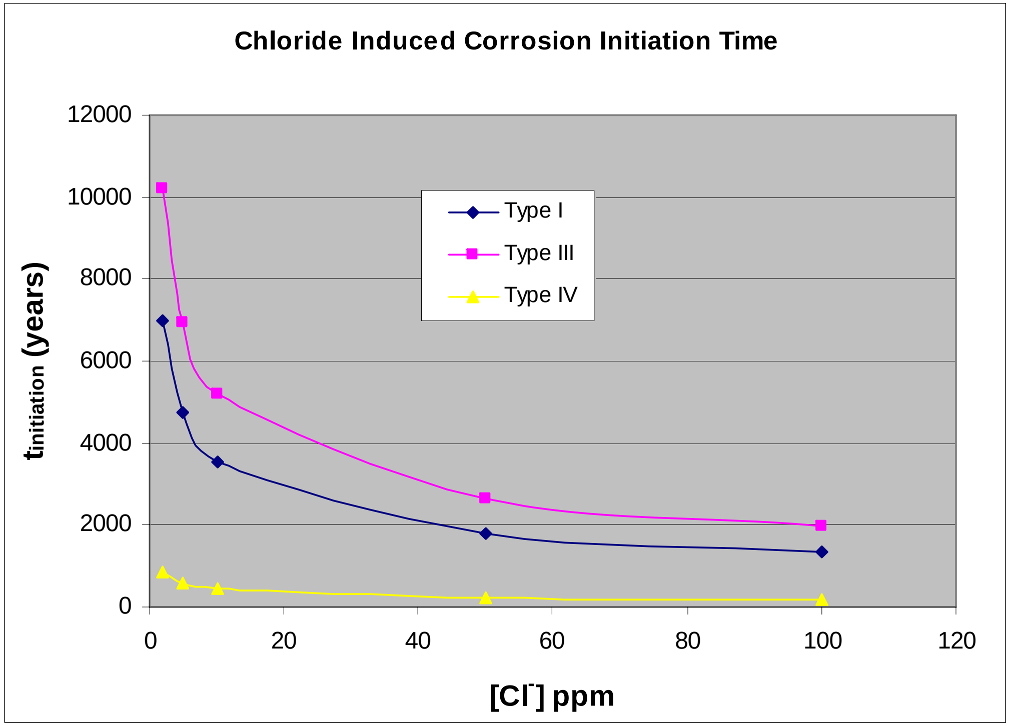
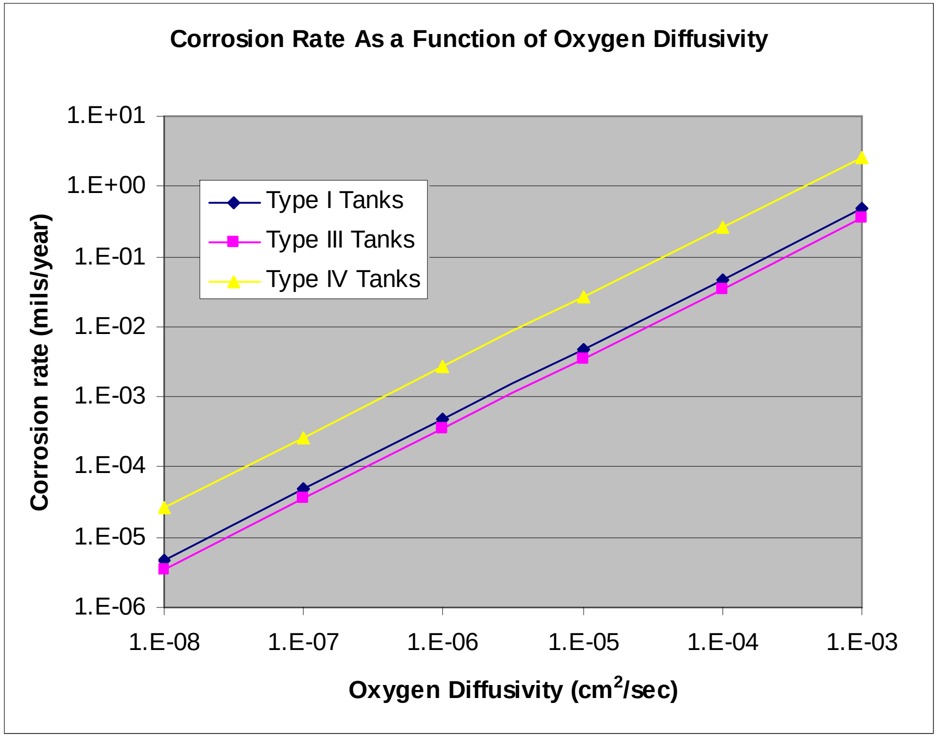
Chloride Induced Corrosion Initiation Time



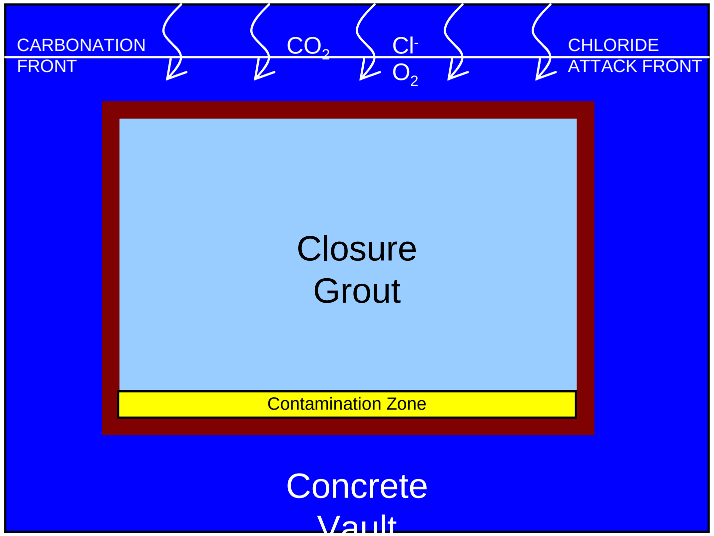
	[Cl$^-$] ppm	$t_{initiation}$ (yrs)
Type I	2	6978
	5	4749
	10	3550
	50	1806
	100	1350
Type III	2	10188
	5	6934
	10	5182
	50	2636
	100	1970
Type IV	2	872
	5	593
	10	444
	50	226
	100	169

Corrosion Rates

- Critical oxygen diffusivity at which the corrosion rate will be greater than 0.04 mils/year corrosion rate:
  - Type I Tank: 8.29×10^{-5} cm^2/sec
  - Type III Tank: 1×10^{-4} cm^2/sec
  - Type IV Tank: 1.51×10^{-5} cm^2/sec



Results of Deterministic Approach



- Initially, general corrosion proceeding at 0.04 mils/year for the tank steel exposed to the concrete/grout.
- Chloride attack then initiated leading to loss of passivity
- Oxygen diffusion for corrosion reactions

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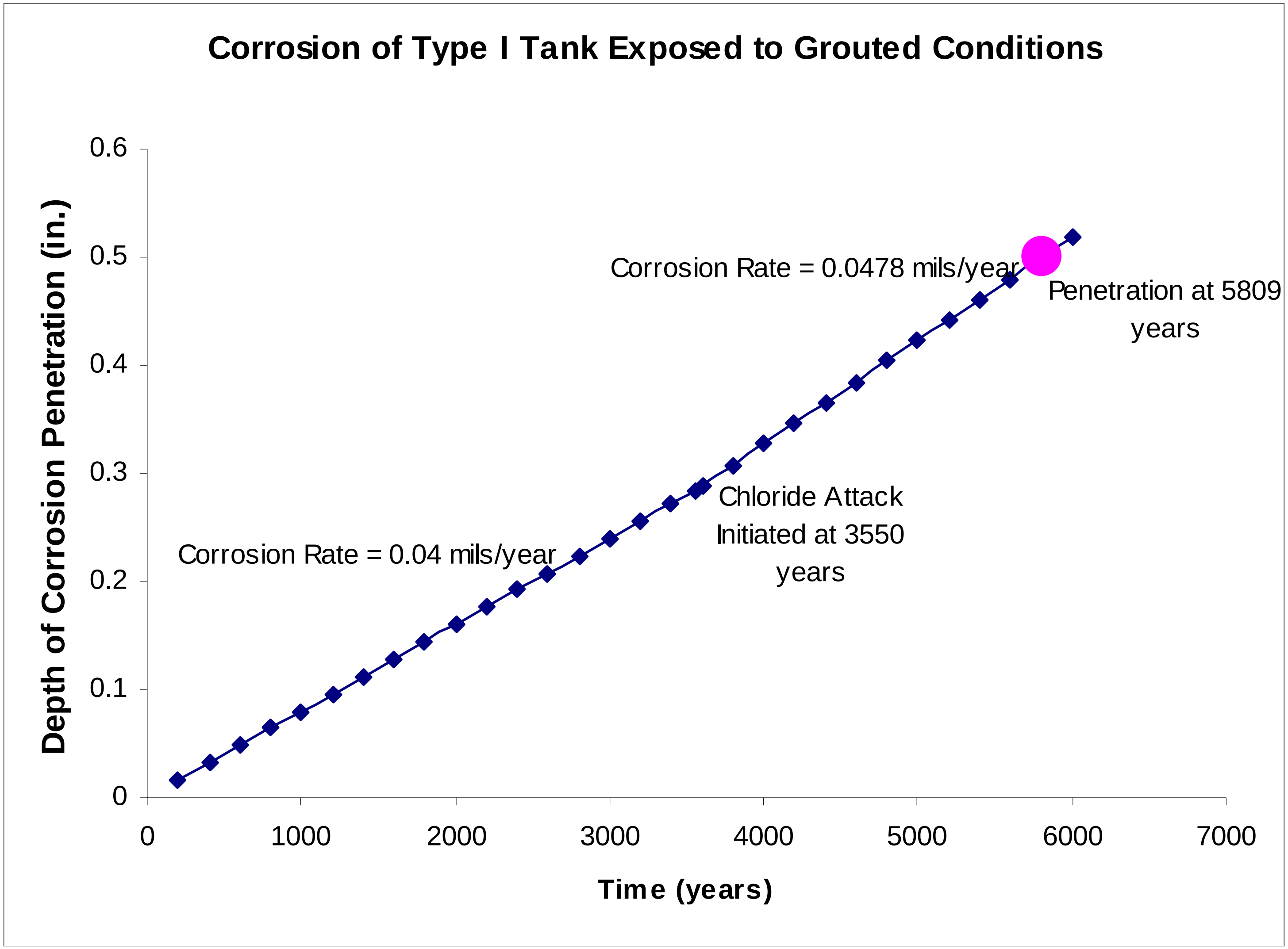
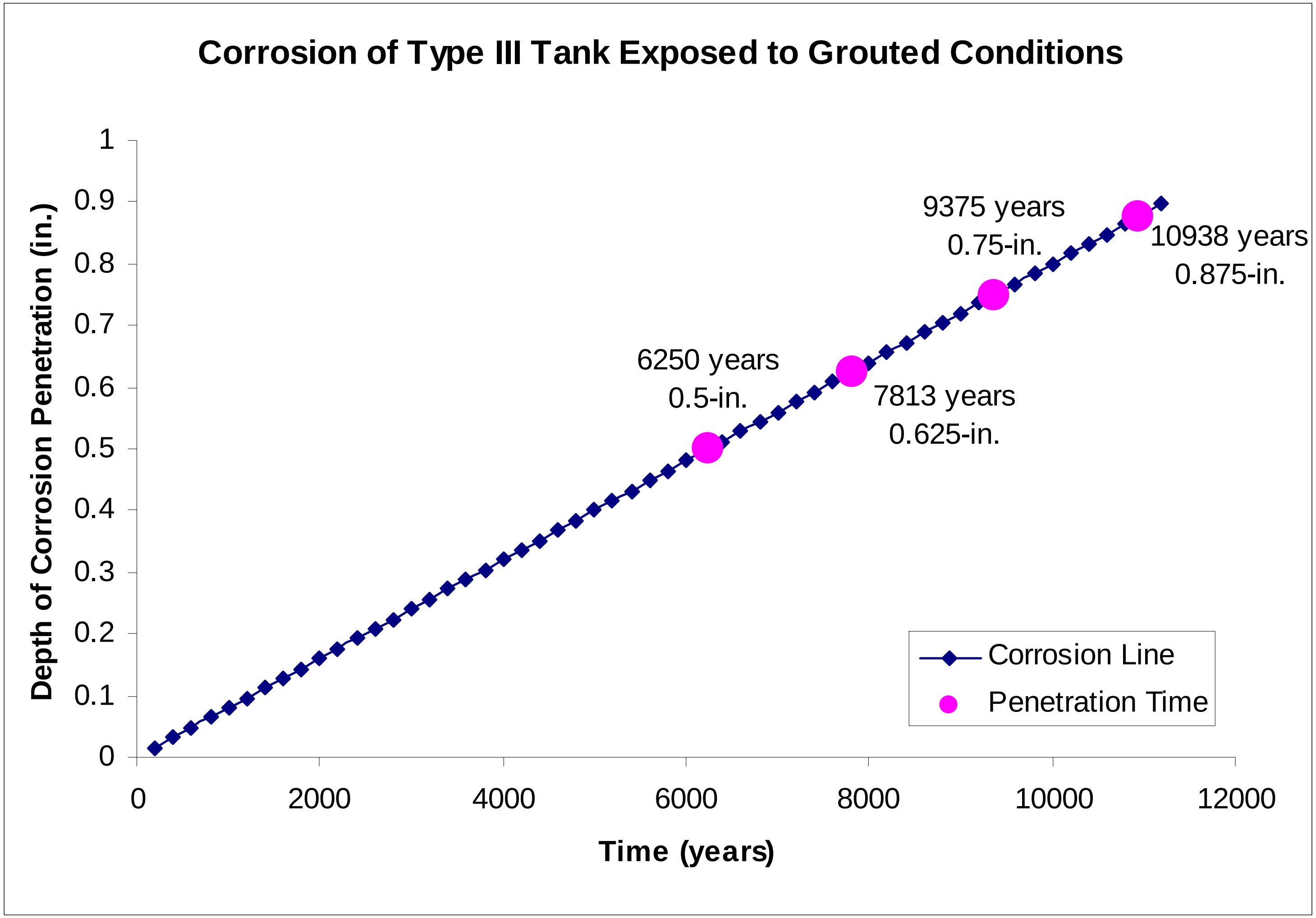
Inputs/Assumptions

- Corrosion is initiated on the both internal and external surfaces of the tank once chloride has penetrated through the thinnest section of concrete.
- Chloride concentration assumed to be 10 ppm
- Oxygen diffusivity is assumed to be 1×10^{-4} cm^2/sec
- Assume that oxygen is available over the entire surface once the oxygen penetrates the thinnest section of concrete, corresponding to the following corrosion rates:
  - Type I Tanks - 0.0478 mils/year
  - Type III Tanks - 0.04 mils/year
  - Type IV Tanks - 0.26 mils/year

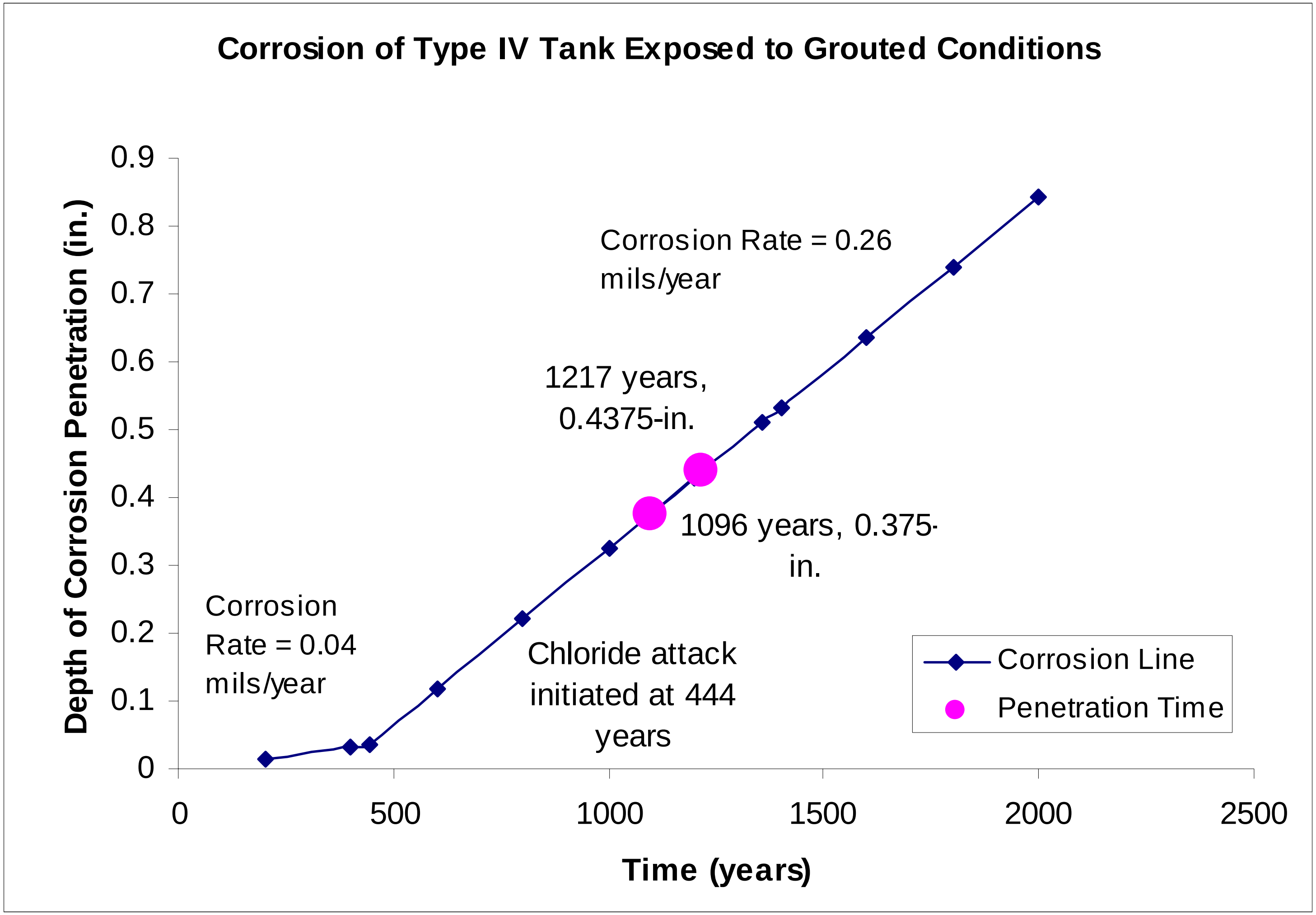
Life Estimation Grouted Conditions: Type I tanks



Life-Estimation Grouted Conditions: Type III Tanks



Life Estimation Grouted Conditions: Type IV Tanks



Life Estimate: Stochastic Approach

- Proposed to account for potential uncertainty in the time-frames proposed for regulatory compliance
- Initially Considered
  - First order reliability methods (FORM)
    - Statistical information is sparse
    - Marginal probability distributions
  - Direct uncertainty analysis
    - Separation of the probability calculations from the evaluation of the performance measure
    - Discretization of the probability intervals
- ***Ultimately, USED Monte Carlo Simulation***
  - Inherently represent the uncertainties in the deterministic approach
  - Large number of simulations
  - Exploits the in-depth knowledge of SRS subsurface environments and HLW tanks as input distributions for the simulations

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Stochastic Technical Approach

- Life of the tank liners was assumed to be a function of the time to corrosion initiation plus the time for corrosion to propagate through the liner
- Grouted Conditions

- General corrosion in grouted conditions
- Chloride induced depassivation, followed by general corrosion
- Carbonation induced loss of protective capacity of the concretecombination

$$t_{failure} = t_{initiation} + \frac{Thickness(mils)}{CorrosionRate(mils / year)}$$

$t_{failure}$ = time to complete consumption of the tank wall by general corrosion
$t_{initiation}$ = time to chloride induced depassivation or carbonation front
Thickness = initial thickness of liner (mils)
Corrosion rate:= Dependent upon condition, i.e. chloride or carbonation

Monte Carlo Models

- Case 1: IF $t_{initiation}$ [Cl^-] ≥ $t_{initiation}$ [Carbonation]

$$t_{failure} = t_{initiation[carbonation]} + \frac{Thickness(mils)}{CorrosionRate(mils/year)}$$

T_0	=	Initial Thickness (mils)
Thickness	=	$T_0 - 0.04 * t_{init[carbonation]}$ [mils]
Corrosion Rate ($R_{carbonation}$)	=	10 mils/year

- Case 2: IF $t_{initiation}$ [Cl^-] < $t_{initiation}$ [Carbonation]

$$t_{failure} = t_{initiation[chloride]} + \frac{Thickness(mils)}{CorrosionRate(mils/year)}$$

T_0	= Initial Thickness (mils)
Thickness	= $T_0 - 0.04 * t_{init[chloride]}$ [mils]
Corrosion Rate ($R_{carbonation}$)	= calculated

$$R_{corrosion} = \frac{4}{3} N_{O_2} \frac{M_{Fe}}{\rho_{Fe}}$$

M_{Fe} = molecular weight of iron (56 g/mol)
ρ_{Fe} = density of iron (7.86 g/cm^3)
N_{O2} = Flux of oxygen through concrete (mol/s/cm^2)

Monte Carlo Models

- Case 3: IF $t_{failure}$ $[Cl^-] \geq t_{initiation\ [Carbonation]}$

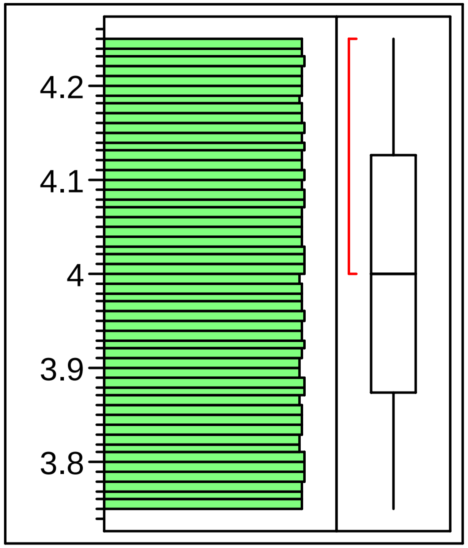
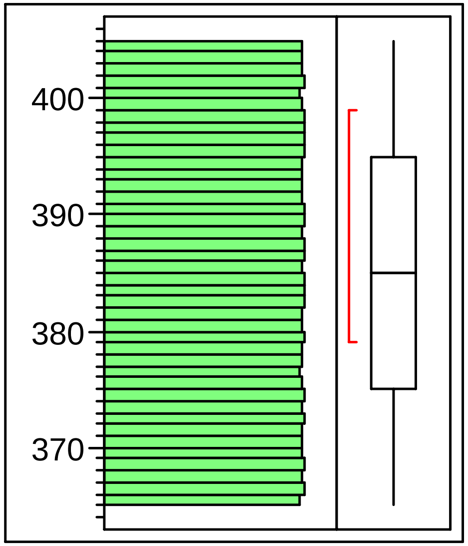
$$t_{failure} = t_{initiation[carbonation]} + \frac{Thickness(mils)}{CorrosionRate(mils/year)}$$

$$T_o - \left\lfloor \left(t_{initiation[carbonation]} - t_{initiation[Cl]} \right) \cdot R_{Cl} + \left(t_{initiation[Cl]} \cdot 0.04 \right) \right\rfloor$$

$$t_{failure} = t_{initiation[carbonation]} + \frac{T_o - \left\lfloor \left(t_{initiation[carbonation]} - t_{initiation[Cl]} \right) \cdot R_{Cl} + \left(t_{initiation[Cl]} \cdot 0.04 \right) \right\rfloor (mils)}{10(mils/year)}$$

- Chloride induced depassivation → corrosion between initiation time to carbonation and initiation time of chloride induced corrosion → corrosion due to carbonation.

Type IV Tank Simulation: Inputs

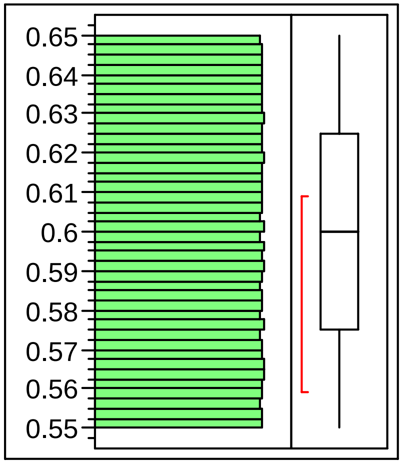
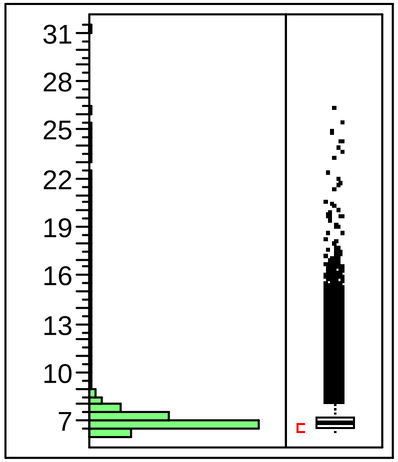
Concrete Vault Thickness (in.)	Steel Liner Thickness (mils)
Uniform Distribution  Min:3.75-in. Median:4-in. Max:4.25-in Mean: 4-in.	Uniform Distribution  Min:365-mils Median:385-mils Max:405-mils Mean: 385 mils

Initiation of Chloride Attack Input Distributions: Type IV

- Chloride Initiation

$$t_{initiation} = \frac{129 \cdot t_c^{\,1.22}}{WCR \cdot \left[Cl^-\right]^{0.42}}$$

$t_{initiation}$ = time required for initiation (years)
t_c = thickness of the concrete cover (in.)
WCR = water-to-cement ratio
[Cl-] = chloride concentration in the groundwater (ppm)

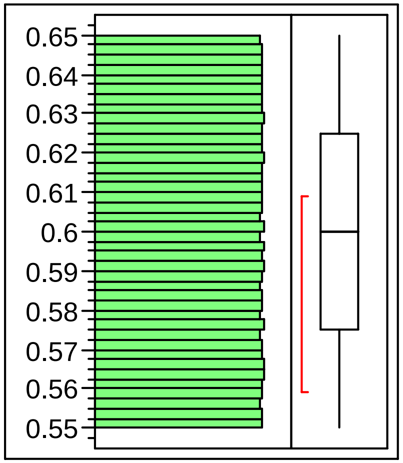
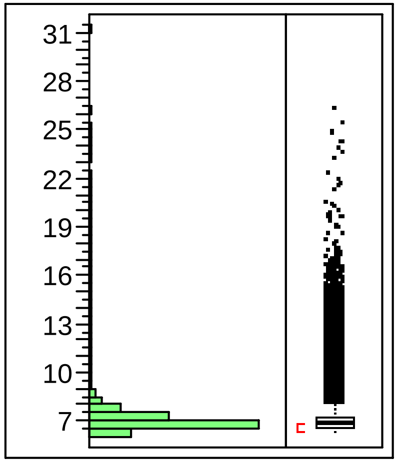
WCR	$[Cl^-]$ (ppm)
Specifications	Measurements
	
Min:0.55	Min:6.249
Median:0.6	Median:6.867
Max:0.65	Max:31.407
Mean: 0.6	Mean: 7.06

Chloride Corrosion Rate Distributions

- Chloride Initiation

$$t_{initiation} = \frac{129 \cdot t_c^{\,1.22}}{WCR \cdot \left[Cl^-\right]^{0.42}}$$

$t_{initiation}$	= time required for initiation (years)
t_c	= thickness of the concrete cover (in.)
WCR	= water-to-cement ratio
[Cl-]	= chloride concentration in the groundwater (ppm)

WCR	**[Cl^-] (ppm)**
Specifications	Measurements
	
Min:0.55	Min:6.249
Median:0.6	Median:6.867
Max:0.65	Max:31.407
Mean: 0.6	Mean: 7.06

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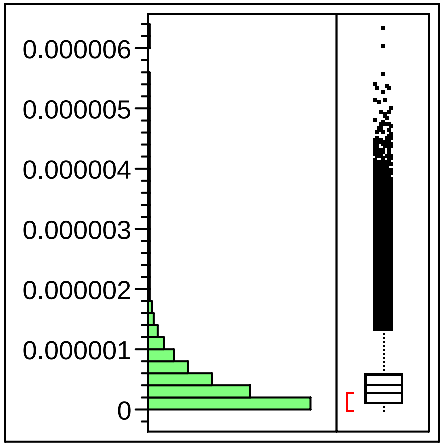
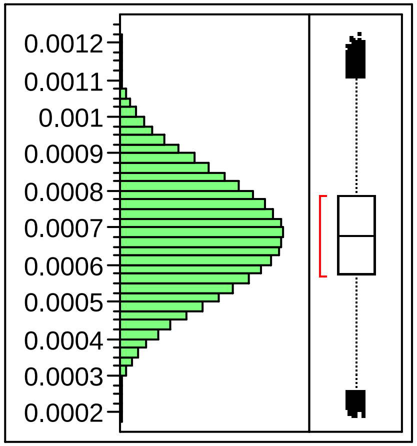
Carbonation Input Distributions: Type IV

- Carbonation: Simple Model

$$X = \left(D_i \frac{C_{gw}}{C_g} t \right)^{\frac{1}{2}}$$

X	=	carbonation depth (cm)
D_i	=	intrinsic diffusion coefficient of Ca^{++} in concrete (cm^2/s)
C_{gw}	=	total inorganic carbon in ground water ($mole/cm^3$)
C_g	=	$Ca(OH)_2$ bulk concentration in concrete solid ($mole/cm^3$)
t	=	time (s)

C_{gw} (mol/cm^3)	C_g:$Ca(OH)_2$ bulk
Measurements	Analytical
	
Min:6.169E-13	Min:0.00019
Median:3.0338E-7	Median:0.00068
Max:6.339E-6	Max:0.0122
Mean: 4.3755E-7	Mean: 0.00068

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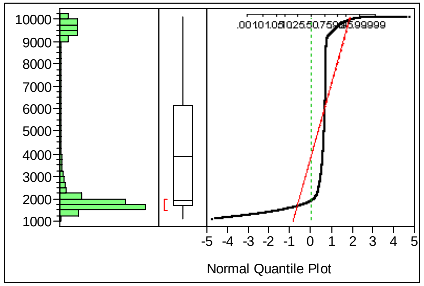
Type IV Results: $D_i(Ca^{++}) = 1x10^{-8} cm^2/sec$, Varied $D_i (O_2)$

Time to Failure: $D_i(O_2)$=0.0001



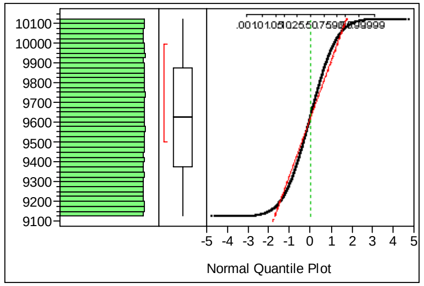
Quantiles

100.0%	maximum	10125
99.5%		10103
97.5%		10014
90.0%		9689
75.0%	quartile	6133
50.0%	median	1920
25.0%	quartile	1678
10.0%		1545
2.5%		1431
0.5%		1346
0.0%	minimum	1110

Moments

Mean	3889.3953
Std Dev	3301.6607
Std Err Mean	3.3016607
upper 95% Mean	3895.8665
lower 95% Mean	3882.9242
N	1000000

Time to Failure: $D_i(O_2)$=0.000001



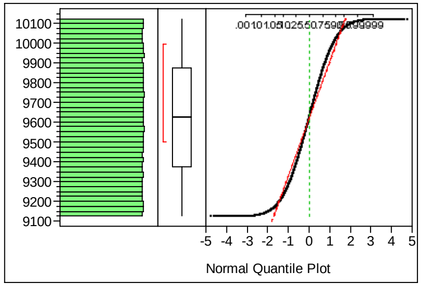
Quantiles

100.0%	maximum	10125
99.5%		10120
97.5%		10100
90.0%		10025
75.0%	quartile	9875
50.0%	median	9626
25.0%	quartile	9376
10.0%		9225
2.5%		9150
0.5%		9130
0.0%	minimum	9125

Moments

Mean	9625.5814
Std Dev	288.30203
Std Err Mean	0.288302
upper 95% Mean	9626.1464
lower 95% Mean	9625.0163
N	1000000

Time to Failure: $D_i(O_2)$=0.00000001



Quantiles

100.0%	maximum	10125
99.5%		10120
97.5%		10100
90.0%		10025
75.0%	quartile	9875
50.0%	median	9626
25.0%	quartile	9376
10.0%		9225
2.5%		9150
0.5%		9130
0.0%	minimum	9125

Moments

Mean	9625.5814
Std Dev	288.30203
Std Err Mean	0.288302
upper 95% Mean	9626.1464
lower 95% Mean	9625.0163
N	1000000

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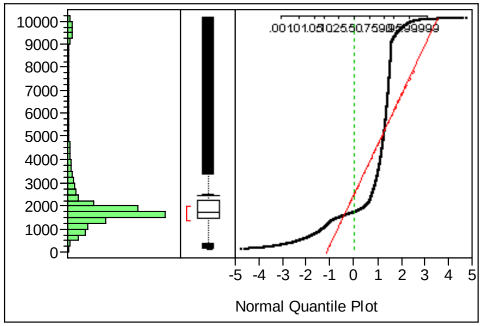
Type IV Results: $D_i(Ca^{++}) = 1x10^{-6}cm^2/sec$, Varied $D_i\ (O_2)$

Time to Failure: $D_i(O_2)$=0.0001



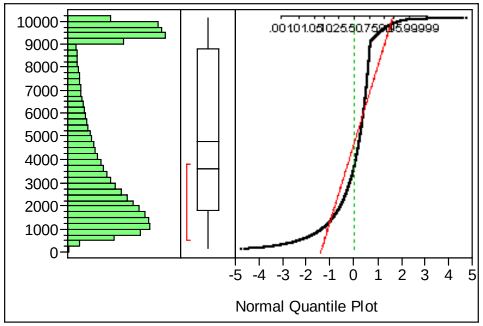
Quantiles

100.0%	maximum	10125
99.5%		10028
97.5%		9656
90.0%		5240
75.0%	quartile	2276
50.0%	median	1754
25.0%	quartile	1509
10.0%		1061
2.5%		654
0.5%		444
0.0%	minimum	152

Moments

Mean	2507.0508
Std Dev	2163.4304
Std Err Mean	2.1634304
upper 95% Mean	2511.291
lower 95% Mean	2502.8105
N	1000000

Time to Failure: $D_i(O_2)$=0.000001



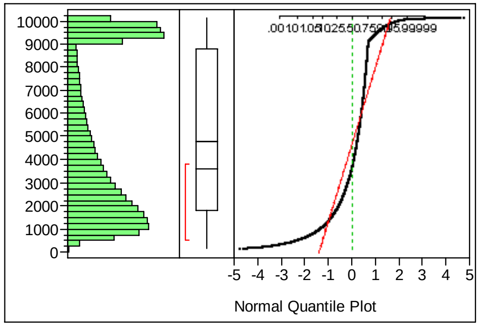
Quantiles

100.0%	maximum	10125
99.5%		10102
97.5%		10012
90.0%		9693
75.0%	quartile	8819
50.0%	median	3638
25.0%	quartile	1805
10.0%		1071
2.5%		655
0.5%		444
0.0%	minimum	152

Moments

Mean	4758.5687
Std Dev	3324.095
Std Err Mean	3.324095
upper 95% Mean	4765.0838
lower 95% Mean	4752.0536
N	1000000

Time to Failure: $D_i(O_2)$=0.00000001



Quantiles

100.0%	maximum	10125
99.5%		10102
97.5%		10012
90.0%		9693
75.0%	quartile	8819
50.0%	median	3638
25.0%	quartile	1805
10.0%		1071
2.5%		655
0.5%		444
0.0%	minimum	152

Moments

Mean	4758.5687
Std Dev	3324.095
Std Err Mean	3.324095
upper 95% Mean	4765.0838
lower 95% Mean	4752.0536
N	1000000

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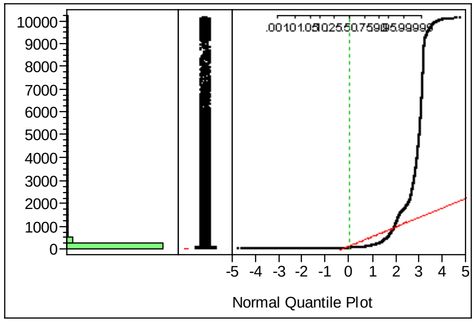
Type IV Results: $D_i(Ca^{++}) = 1x10^{-4} cm^2/sec$, Varied $D_i(O_2)$

Time to Failure: $D_i(O_2)$=0.0001



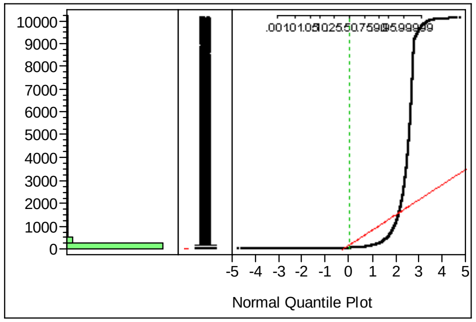
Quantiles

100.0%	maximum	10124
99.5%		2119
97.5%		1041
90.0%		280
75.0%	quartile	126
50.0%	median	75
25.0%	quartile	56
10.0%		49
2.5%		45
0.5%		42
0.0%	minimum	38

Moments

Mean	168.94462
Std Dev	420.1519
Std Err Mean	0.4201519
upper 95% Mean	169.76811
lower 95% Mean	168.12114
N	1000000

Time to Failure: $D_i(O_2)$=0.000001



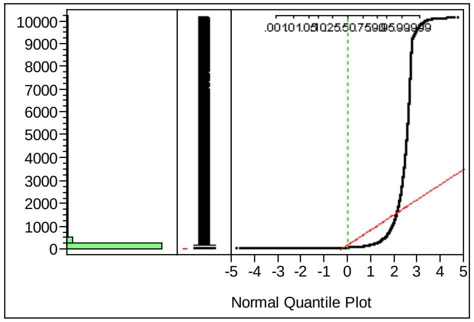
Quantiles

100.0%	maximum	10125
99.5%		5107
97.5%		1050
90.0%		280
75.0%	quartile	126
50.0%	median	75
25.0%	quartile	56
10.0%		49
2.5%		45
0.5%		42
0.0%	minimum	38

Moments

Mean	200.11287
Std Dev	677.54184
Std Err Mean	0.6775418
upper 95% Mean	201.44083
lower 95% Mean	198.78491
N	1000000

Time to Failure: $D_i(O_2)$=0.00000001



Quantiles

100.0%	maximum	10125
99.5%		5107
97.5%		1050
90.0%		280
75.0%	quartile	126
50.0%	median	75
25.0%	quartile	56
10.0%		49
2.5%		45
0.5%		42
0.0%	minimum	38

Moments

Mean	200.11287
Std Dev	677.54184
Std Err Mean	0.6775418
upper 95% Mean	201.44083
lower 95% Mean	198.78491
N	1000000

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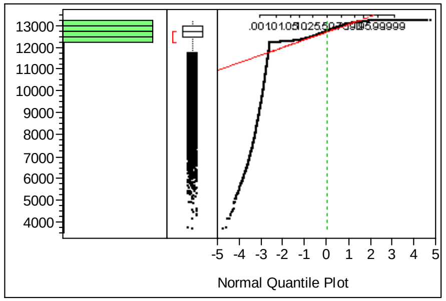
Recommendations

- $D_i\ (Ca^{2++}) = 1\text{x}10^{-6}$ cm2/sec
- $D_i\ (O_2) = 1\text{x}10^{-6}\ cm_2$/sec

Type I Tank Failure Distribution



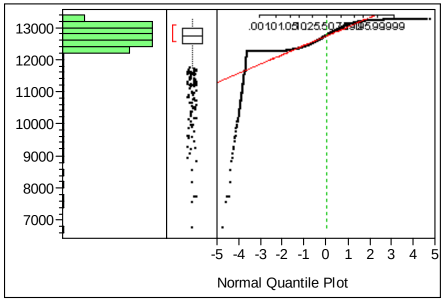
Quantiles

100.0%	maximum	13250
99.5%		13245
97.5%		13225
90.0%		13149
75.0%	quartile	12999
50.0%	median	12747
25.0%	quartile	12496
10.0%		12346
2.5%		12270
0.5%		12250
0.0%	minimum	3717

Moments

Mean	12737.745
Std Dev	352.92285
Std Err Mean	0.3529229
upper 95% Mean	12738.437
lower 95% Mean	12737.053
N	1000000

Type III Tank Failure Distribution



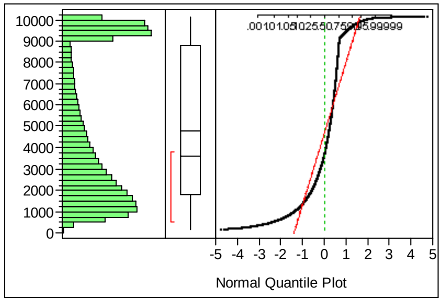
Quantiles

100.0%	maximum	13250
99.5%		13245
97.5%		13225
90.0%		13150
75.0%	quartile	13000
50.0%	median	12751
25.0%	quartile	12500
10.0%		12351
2.5%		12275
0.5%		12255
0.0%	minimum	6789

Moments

Mean	12749.991
Std Dev	289.40127
Std Err Mean	0.2894013
upper 95% Mean	12750.558
lower 95% Mean	12749.424
N	1000000

Type IV Tank Failure Distribution



Quantiles

100.0%	maximum	10125
99.5%		10102
97.5%		10012
90.0%		9693
75.0%	quartile	8819
50.0%	median	3638
25.0%	quartile	1805
10.0%		1071
2.5%		655
0.5%		444
0.0%	minimum	152

Moments

Mean	4758.5687
Std Dev	3324.095
Std Err Mean	3.324095
upper 95% Mean	4765.0838
lower 95% Mean	4752.0536
N	1000000

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Summary

- Estimate lifetime of tank steel for performance assessment for tank closure
- Deterministic and Stochastic approaches
- Accounted for corrosion of tank steel liner in contact with grout/concrete
- Data will be used as input into groundwater modeling efforts: PORFLOW and GOLDSIM

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